Appendix A
Kronecker Product

A.1 Definition

Let A be a $n \times n$ matrix (with entries a_{ij}) and let B be a $m \times m$ matrix. Then the *Kronecker product* of A and B is the $mn \times mn$ block matrix

$$\mathsf{A} \otimes \mathsf{B} = \begin{pmatrix} a_{11}\mathsf{B} & \cdots & a_{1n}\mathsf{B} \\ \vdots & \ddots & \vdots \\ a_{n1}\mathsf{B} & \cdots & a_{nn}\mathsf{B} \end{pmatrix}. \tag{A.1}$$

The Kronecker product is also known as the *direct product* or the *tensor product* [112, 345, 224].

$$\mathbf{z} = \mathbf{x} \otimes \mathbf{y} = (x_1 y_1, \ldots, x_1 y_m, \ldots, x_n y_1, \ldots, x_n y_m)^T, \tag{A.2}$$

$$(\mathsf{A} \otimes \mathsf{B})\mathbf{z} = (\mathsf{A} \otimes \mathsf{B})(\mathbf{x} \otimes \mathbf{y}) = (\mathsf{A}\mathbf{x}) \otimes (\mathsf{B}\mathbf{y}). \tag{A.3}$$

A.2 Fundamental Properties

1. The product is bilinear. If k is a scalar, and A, B, and C are square matrices, such that B and C are of the same dimension, then

$$\mathsf{A} \otimes (\mathsf{B} + \mathsf{C}) = \mathsf{A} \otimes \mathsf{B} + \mathsf{A} \otimes \mathsf{C}, \tag{A.4}$$

$$(\mathsf{B} + \mathsf{C}) \otimes \mathsf{A} = \mathsf{B} \otimes \mathsf{A} + \mathsf{C} \otimes \mathsf{A}, \tag{A.5}$$

$$k(\mathsf{A} \otimes \mathsf{B}) = (k\mathsf{A}) \otimes \mathsf{B} = \mathsf{A} \otimes (k\mathsf{B}). \tag{A.6}$$

2. If A, B, C, and D are square matrices such that the products AC and BD exist, then $(\mathsf{A} \otimes \mathsf{B})(\mathsf{C} \otimes \mathsf{D})$ exists and

$$(\mathsf{A} \otimes \mathsf{B})(\mathsf{C} \otimes \mathsf{D}) = \mathsf{AC} \otimes \mathsf{BD}. \tag{A.7}$$

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If A and B are invertible matrices, then

$$(\mathsf{A} \otimes \mathsf{B})^{-1} = \mathsf{A}^{-1} \otimes \mathsf{B}^{-1}. \tag{A.8}$$

3. If A and B are square matrices, then for the transpose we have

$$(\mathsf{A} \otimes \mathsf{B})^{T} = \mathsf{A}^{T} \otimes \mathsf{B}^{T}. \tag{A.9}$$

4. Let A and B be square matrices of dimensions n and m. If $\{\lambda_i | i = 1, \ldots, n\}$ are the eigenvalues of A and $\{\mu_j | j = 1, \ldots, m\}$ are the eigenvalues of B, then $\{\lambda_i \mu_j | i = 1, \ldots, n, \ j = 1, \ldots, m\}$ are the eigenvalues of $\mathsf{A} \otimes \mathsf{B}$. Also,

$$\det(\mathsf{A} \otimes \mathsf{B}) = (\det \mathsf{A})^{m} (\det \mathsf{B})^{n}, \tag{A.10}$$

$$\operatorname{rank}(\mathsf{A} \otimes \mathsf{B}) = \operatorname{rank} \mathsf{A} \, \operatorname{rank} \mathsf{B}, \tag{A.11}$$

$$\operatorname{tr}(\mathsf{A} \otimes \mathsf{B}) = \operatorname{tr} \mathsf{A} \, \operatorname{tr} \mathsf{B}. \tag{A.12}$$

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